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PREPRINT

Stable Isotope and Groundwater Flow Dynamics of Agricultural Irrigation Recharge into Groundwater Resources of the Central Valley, California

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1. Abstract

Intensive agricultural irrigation and overdraft of groundwater in the Central Valley of California profoundly affect the regional quality and availability of shallow groundwater resources. Associated changes in the isotopic character of the water can be used with great advantage to monitor and evaluate these undesirable effects. In the natural state, the $\delta^{18}O$ values of groundwater were relatively homogeneous (mostly -7.0 ±0.5‰), reflecting local meteoric recharge that slowly (1-3m/yr) flowed toward the valley axis. Today, on the west side of the valley, the isotope distribution is dominated by high ^{18}O enclosures formed by recharge of evaporated irrigation waters, while the east side has bands of low ^{18}O groundwater indicating induced recharge from rivers draining the Sierra Nevada mountains. Changes in $\delta^{18}O$ values caused by the agricultural recharge strongly correlate with elevated nitrate concentrations (5 to >100 mg/L) that form pervasive, non-point source pollutants. Small, west-side cities dependent solely on groundwater resources have experienced increases of >1.0 mg/L per year of nitrate for 10-30 years. The resultant high nitrates threaten the economical use of the groundwater for domestic purposes, and have forced some well shut-downs. Furthermore, since >80% of modern recharge is now derived from agricultural irrigation, and because modern recharge rates are ~10 times those of the natural state, agricultural land retirement by urbanization will severely curtail the current safe-yields and promote overdraft pumping. Such overdrafting has occurred in the Sacramento metropolitan area for ~40 years, creating cones of depression ~25m deep. Today, groundwater withdrawal in Sacramento is approximately matched by infiltration of low ^{18}O water (-11.0‰) away from the Sacramento and American Rivers, which is estimated to occur at 100-300m/year from the sharp ^{18}O gradients in our groundwater isotope map.

2. Introduction

The population of California experienced a 30% increase during the 1980's that, combined with a prolonged drought (1987-1992), resulted in increased degradation of the existing groundwater resources. In the recent past concerns for groundwater contamination focused primarily on small point-source pollutants. Today, non-point source pollution is the principal threat to regional groundwater quality, and overdraft and land subsidence are continuing threats to the use of groundwater supplies.

This paper details results from regional isotope surveys of the groundwater resources of the Central Valley, in particular the southern Sacramento Valley and the northern San Joaquin Valley. Potable groundwater supplies reside in Pliocene-Holocene-age alluvial aquifers ranging up to 1000m deep, but most pumping is from depths between 30 and 300m below the surface. For the last century, the Central Valley of California has mostly been used for intensely irrigated agriculture and, less commonly, for livestock grazing, but in recent years the valley has increasingly become urbanized by outward population growth of the San Francisco Bay Area and the cities of Sacramento and Stockton. We focus in this report on 1) the natural recharge and flow of the groundwater as derived from isotope data, 2) the effects of prolonged agricultural irrigation on groundwater quality in the valley, and 3) the response of the groundwater supply to conversion from agricultural to urban land use.

3. δ^{18}O Variations in Central Valley Groundwater

The δ^{18}O values of Central Valley groundwater exhibit regular geographic patterns that not only produce an "image" of the groundwater , but provide direct evidence on the dynamic nature of its recharge and flow (Fig. 1). For instance, on the west side of the valley, where the potentiometric surface has a regular eastward slope, the contoured δ^{18}O values form two large high ^{18}O (≥-6.0‰) enclosures that stretch from Cache Creek on the north to the Sacramento-San Joaquin Delta on the south. Further south in the Brentwood region, where the potentiometric surface also slopes eastward, the groundwater is dominated by a small low ^{18}O enclosure (≤-8.5‰).

All the ^{18}O enclosures on the west side of the valley record decades of recharge from diverted surface water used for agricultural irrigation. Lake Berryessa Reservoir water (-3 to -5‰ in δ^{18}O) was diverted south via Putah Creek and by canals to reduce the groundwater demand, creating the large high δ^{18}O zone from Fairfield to Davis that contrasts with the pristine meteoric groundwater of approximately -7.5‰. A similar diversion of Cache Creek water (δ^{18}O= -5 to 0‰)

for irrigation created the prevalent high ^{18}O zone northwest of Davis and represents >100 years of recharge.

On the east side of the Central Valley, the potentiometric surface is defined by large (~3000km^{2}) cones of depression stretching from north of the Sacramento metropolitan area to south of the Stockton region. These cones are interrupted only where major westward flowing rivers occur. The low δ^{18}O isopleths near Sacramento, reflecting recharge of -11.0‰ water from the Sacramento and American Rivers, parallel the cones of depression.

4. Natural Groundwater

4.1 General Sources and Apparent Ages

The δ^{18}O values of precipitation decrease from about -6‰ in coastal California to -12‰ or less at high altitudes in the Sierra Nevada mountains, following typical geographic patterns [1]. In the Central Valley, shallow *natural* groundwater (90-300m) generally falls on or slightly to the right of the global meteoric water line and has δ^{18}O values ranging between -6.5 and -9.0‰ that represent the average value of proximal meteoric recharge [2]. Apparent ^{14}C ages of natural groundwater typically exceed 1500 years but have not been observed beyond 17,000 years. Groundwater with apparent ^{14}C ages of Pleistocene-age in the southern Sacramento Valley is depleted in δ^{18}O by ~2.0‰ relative to the local mean precipitation values [2], suggesting that the local climatic conditions have changed.

4.2 Sources of Carbon

Natural vegetation in the Central Valley follows C_3 and C_4 metabolic pathways that respire CO_2 with variable δ^{13}C values [3]. The δ^{13}C values of groundwater (Table 1) indicate bicarbonate equilibration with soil CO_2, followed by partially-closed dissolution of soil zone carbonate into recharge groundwater [e.g. 4-5]. Carbonate exchange with the water is primarily limited to the first few meters during recharge and enrichment of the δ^{13}C values with groundwater age is not apparent (Table 1). Enrichment is not expected primarily because of the predominantly siliciclastic sediments of the valley fill. In the Sacramento samples, however, a depleted δ^{13}C occurs, suggesting that ^{14}C "dead" organic matter has been incorporated into the DIC of the groundwater. For simplicity, a Vogel model [6] has been applied to the ^{14}C concentrations in the groundwater using an initial ^{14}C value of 85 pmc to approximate the incorporation of dead inorganic carbon. Empirical data [7] support the use of this initial value, where observations of pre-1950's agriculturally recharged groundwater has an average ^{14}C concentration of 85 pmc. For the Sacramento samples, a combined Vogel and Pearson model [8] has been applied (Table 1). Here, after partially closed system exchange with soil carbonate, the dissolved carbon is assumed to slowly incorporate "dead" organic carbon, having a mean $\delta^{13}C$ value of -28‰ [9], during flow in the saturated zone.

4.3 Implications for Natural Flow

The rate of vertical flow of Central Valley groundwater can be inferred from the model ^{14}C ages. The results are variable, with the available data tending to fall on either of two trends (Fig. 2). Groundwaters from the Brentwood region and the Sacramento area fall on a low-slope trend that suggests a lower average vertical migration rate than the deeper groundwater of Yolo County. Shallow groundwaters of Yolo County fall on both the low-slope and high-slope trends.

It is interesting to note that Yolo County sample SV-JF-9-91 is meteoric in character, yet is 1.2‰ lower in ^{18}O than local modern mean precipitation [2]. Even though the sample occurs at a depth of only ~100m, it is part of a group of low ^{18}O samples that mostly represent deep wells (>350m below the surface; e.g. samples DW-2, DW-5, and DW-6A). These low ^{18}O groundwaters indicate different climatic conditions in the past, and their segregation with depth attests to the variable flow rates in the groundwater basin of Yolo County.

Surface geologic deposits provide direct physical evidence for why the variable migration rates exist in the Central Valley. Potable groundwater resides in fluvial deposits that range in age from Late Pliocene to Holocene [10], and these deposits are typically divided into 1) the Plio-Pleistocene Tehama and Tulare Formations, and 2) overlying Late Pleistocene-Holocene deposits. Groundwaters sampled in the Brentwood region are primarily derived from the Late Pleistocene-Holocene deposits which directly onlap Eocene marine rocks of the Coast Ranges, so surface exposures of the Plio-Pleistocene Formation are absent. Groundwater in Yolo County is derived from both the Plio-Pleistocene Formation and the younger deposits. Unlike the Brentwood area, the western edge of Yolo County has a broad exposure of Pio-Pleistocene Tehama Formation that typically hosts coarse gravel lenses. This thick fluvial deposit also blankets the subsurface in the Yolo County region where it gives rise to potable aquifers up to great depths (1000m below the surface). In addition, these older fluvial deposits are probably coarse-grained on average, and they therefore can support the higher vertical migration rates calculated from the model ^{14}C ages.

5. Modern Agricultural Recharge and Its Relation to Nitrate Contamination

5.1 Nitrate in Groundwater

California irrigates 40,000 km^2 of farm land on average per year, requiring 43 billion cubic meters of water [11], that results in a multi-billion dollar state industry. At least 40% of the agricultural water demand is supplied by groundwater resources [12]. Irrigation is in the form of flood-type for rice crops, or more commonly as furrow flooding for row crops. Annual requirements range from 0.3-2.5m of applied water and average approximately 1.1m, with the amount depending mostly on soil type, which commonly ranges from silty to clay loams or clays. At present, the downward percolation of excess agricultural irrigation water constitutes >80% of the annual groundwater recharge to the Central Valley [7, 15].

The large-scale addition of nitrogen fertilizers (mostly anhydrous ammonia) to irrigation water, termed "fertigation", has existed for decades and today is pervasive throughout the Central Valley. Non-point source nitrate pollutants exist in groundwater beneath many areas of the valley, as exemplified by the Brentwood region (Fig. 3). Nitrate concentrations range from 0 to >100 mg/L as NO_3 in groundwaters sampled from the surface to >100m in depth in some parts of the Central Valley [e.g. 13, 2]. Nitrate concentrations have been steadily rising at a rate between 0.25 to >1.0 mg/L per year in municipal groundwaters since the early 1960’s (Fig. 4a and 4b).

Multiple sources for nitrate pollution in groundwater have been suggested [e.g. 14] including septic tanks, barnyards, and fertilizers. Some elementary observations point to agricultural activity and particularly to fertilizers as the predominant source of this nitrate. For instance, increasing nitrate concentrations in the groundwater are matched by a proportional increase or decrease of the $\delta^{18}O$ value relative to local pristine meteoric groundwater (Fig. 4c and 4d), depending on the source of the applied irrigation water. Thus a negative correlation between nitrate concentrations and $\delta^{18}O$ is found in the Brentwood region, where low $\delta^{18}O$ waters from the Sierras have been imported for irrigation. In contrast, in the Davis area, groundwater recharged from agricultural irrigation has been evaporatively enriched to high $\delta^{18}O$ values relative to local pristine groundwater, so that a positive correlation is found [2]. All agriculturally recharged groundwater is also matched by younger apparent ^{14}C ages [15].

5.2 Rates of Modern Recharge

Central Valley groundwater comprising ~100% agriculturally recharged water is observed on average to a depth of ~45m below the surface [2, 7]. In the Brentwood region, agricultural irrigation began ~80 years ago with the completion of a diversion canal through the area. The simplest calculation indicates that the mean vertical recharge rate is ~56cm/yr, or ~17cm/yr given a mean porosity of 30% in the sediments [7]. This suggests that the crops are ~72% efficient with the 60cm/yr applied irrigation water. This rate of vertical infiltration is >10 times the mean vertical recharge rates calculated from the ^{14}C ages for the pristine groundwaters in the natural state (Table 1). In Yolo County, the higher recharge rate sustains the high agricultural and urban groundwater demands, and in addition forms increased hydrologic gradients and increases the rates of lateral groundwater flow, which typically exceeds 30m/yr [16, 2, 15]. Simultaneous groundwater pumping and irrigation recharge represents a new type of groundwater "mining" that produces no apparent change in storage of the aquifers [15]. These effects are observed only on the west side of the Central Valley where agricultural irrigation is predominant.

6. Municipal Groundwater Resources

6.1 Small Urban Areas

The disturbed $\delta^{18}O$ patterns in Central Valley groundwater are direct results of the different sources of the modern recharge, which are ultimately linked to 1) land use development in the respective regions and 2) groundwater resource utilization. For example, west side valley land use directly impacts water quality for the cities of Davis, Woodland, and Brentwood (Figs. 4a and 4b), which are centered in large regions of intensely irrigated farmland that have been flood irrigated for >75 years. At present, Davis and Woodland each incorporate 50,000 people in areas of approximately $25km^2$, while Brentwood incorporates 10,000 people within $5km^2$. The current growth rates of Davis (3%), Woodland (3%), and Brentwood (10%) will urbanize an additional ~$80km^2$ of irrigated farm land over the next 25 years. In 2020 AD, urban parts Yolo County and the Brentwood region may respectively incorporate 10 and 50% of the total land surface area.

With this dramatic expansion of urban areas and the associated retirement of agricultural land, the abnormally high recharge rates observed today will not be sustained. In fact, recharge may decrease back to or below the natural rates (Table 1) within the urban areas. Alternative water resources are therefore necessary to sustain this planned urban growth. As an example, we have developed a simple model to illustrate the change in groundwater safe yield as land is converted from agricultural to urban use in the Brentwood region (Fig. 5). Lines (a) and (b) were calculated assuming recharge is available over the entire $67km^2$ area and groundwater would flow from outlying agricultural fields toward the urban areas. Lines (a) and (b) suggest that only ~14% of the total water demand will ultimately be met as population climbs to 70,000. Line (c) was calculated considering a total land area of $33.5km^2$, and ignores groundwater contribution from the outlying agricultural regions. This results in a "worst case" scenario for safe yields in urban pumping, and provides only ~2% of the total water demand for a population of 70,000. The $33.5km^2$ is also equivalent to total land urbanization for a projected population of ~70,000.

6.2 Sacramento Metropolitan Area

On the east side of the Central Valley, the City of Sacramento stands as an example of a large urbanized area that incorporates far more land surface than irrigated farm land in the immediately outlying regions. The Sacramento metropolitan area and the suburban areas stretching along the American River drainage to the northeast (Fig. 1), total an estimated 675,000 people. Total groundwater demands are calculated to be 113 million m^3/yr over the entire region. This annual groundwater withdrawal is 18cm, equivalent to an average drawdown of 60cm/yr in a layer of 30% porosity.

For the past 40 years a cone of depression beneath the Sacramento area has been developing, with initial yearly water level drops of 0.5 to 1.0m/yr. This rate of head drop decreased in recent years and today the cone of depression is essentially maintained at around a maximum depth of 25m below the surface (or 15 meters below sea level). Modern recharge from surface precipitation is negligible in the Sacramento area because urbanization of the land surface has greatly increased storm runoff. In addition, the $\delta^{18}O$ values of groundwater beneath the Sacramento area indicate that recharge from the Sacramento and American rivers is the only significant source of groundwater replenishment.

If the water table is taken to be at a steady state level, and if it is assumed that 100% of groundwater recharge is derived from the Sacramento and American Rivers, then a simple model of yearly influx from the rivers can be calculated and compared to the lateral extent modern river water is observed in the groundwater today. Assuming simplistically that surface water is lost uniformally to the groundwater laterally from the rivers, then ~80km of river length is available for recharge. If river water loss occurs over a range of 15 to 50m depth, and if the average porosity is 30%, then a uniform lateral flow rate of 100 to 300m/yr is sufficient to account for all of the estimated 1 billion m^3 of groundwater pumped over the last 10 years. Assuming that the current total groundwater discharge rate has been maintained for 10 years, the scale of lateral flow is approximately 1 to 3km. This distance is equivalent to the interior distance river water is observed in groundwater today (Fig. 1).

7. Acknowledgments

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8. References

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Figure Captions

Figure 1. The variations in $\delta^{18}O$ values of Central Valley groundwater form regular contour patterns. The $\delta^{18}O$ enclosures on the west side of the valley contrast the generally eastward sloping water table, and are mostly caused by decades of recharge of evaporated surface water derived from irrigated fields. Low ^{18}O river water recharges the east side of the valley, forming $\delta^{18}O$ contours that generally parallel cones of depression formed by regional groundwater overdraft. "W" equals the City of Woodland.

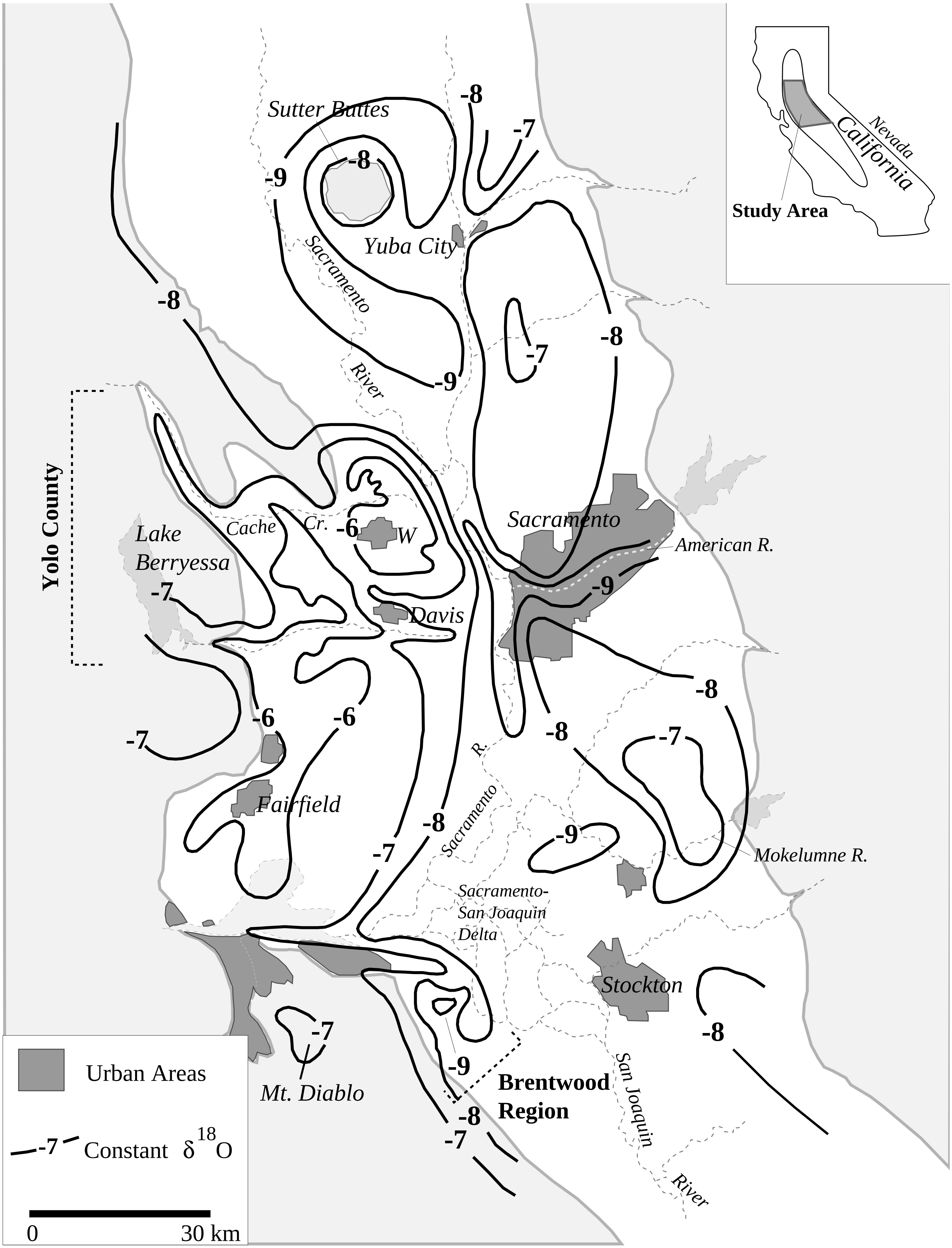
Figure 2. Graph showing variations of ^{14}C ages with sample depth. Surface exposure of higher permeability Plio-Pleistocene deposits in western Yolo County promote faster vertical groundwater flow rates than occur for the groundwater in overlying Pleistocene-Holocene alluvium in Sacramento, the Brentwood region, and most of Yolo County.

Figure 3. Dissolved nitrate concentrations in Central Valley groundwater represent the most significant non-point source pollutant that threatens the potability of groundwater supplies. This example from the Brentwood region shows the pervasiveness of elevated nitrate concentrations that can be directly linked to decades of fertilizer application. Samples are mostly collected from singly-perforated domestic supply wells of low pumping capacity.

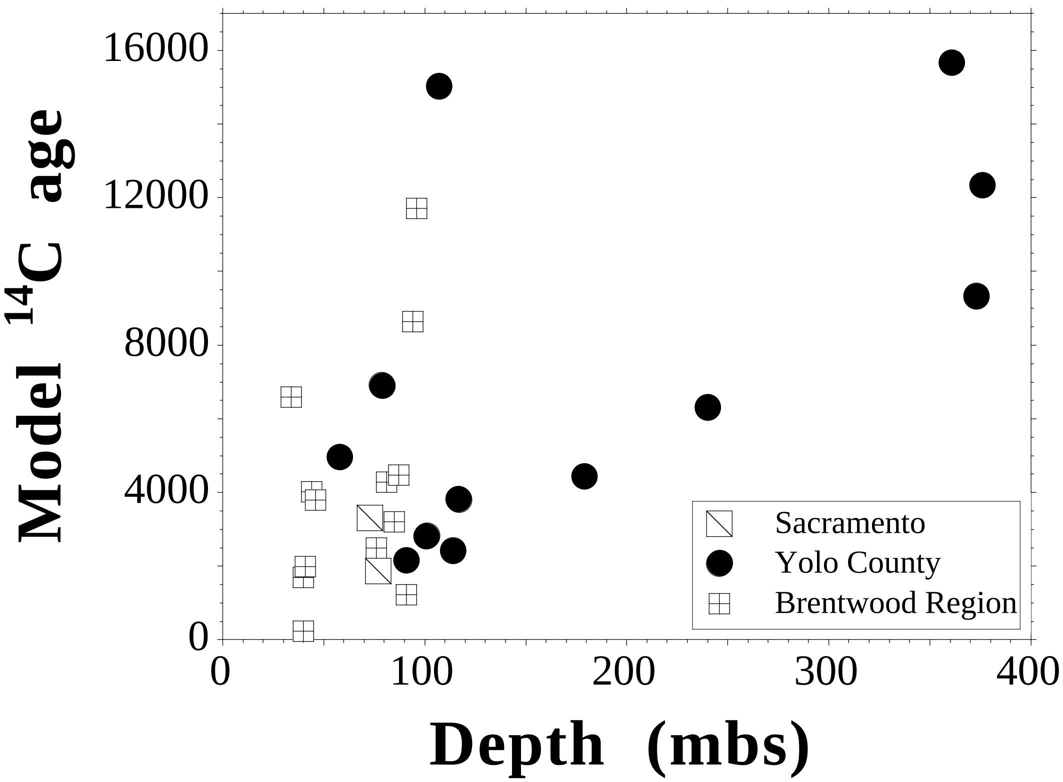
Figure 4. (a) Dissolved nitrate concentrations in the City of Brentwood municipal wells have been increasing at rates exceeding 1.0 mg/L per year. This has forced shut down of most existing wells (solid dots) in the mid to late 1980s and the drilling of new wells (open symbols). (b) Data collected in 1994 show that the nitrate concentrations increase with decreasing $\delta^{18}O$ values of the groundwater. Agricultural irrigation water has been applied for ~80 years in this region, and because it is derived from the Sierra Nevada, it has a low mean $\delta^{18}O$ value of -9.2‰. (c) The City of Davis is experiencing increasing nitrate levels in municipal wells at similar rates to Brentwood. (d) Data collected in 1990-1991 in Davis municipal wells show that nitrate concentrations increase with increasing $\delta^{18}O$ values. The higher $\delta^{18}O$ values can be attributed to recharged irrigation water

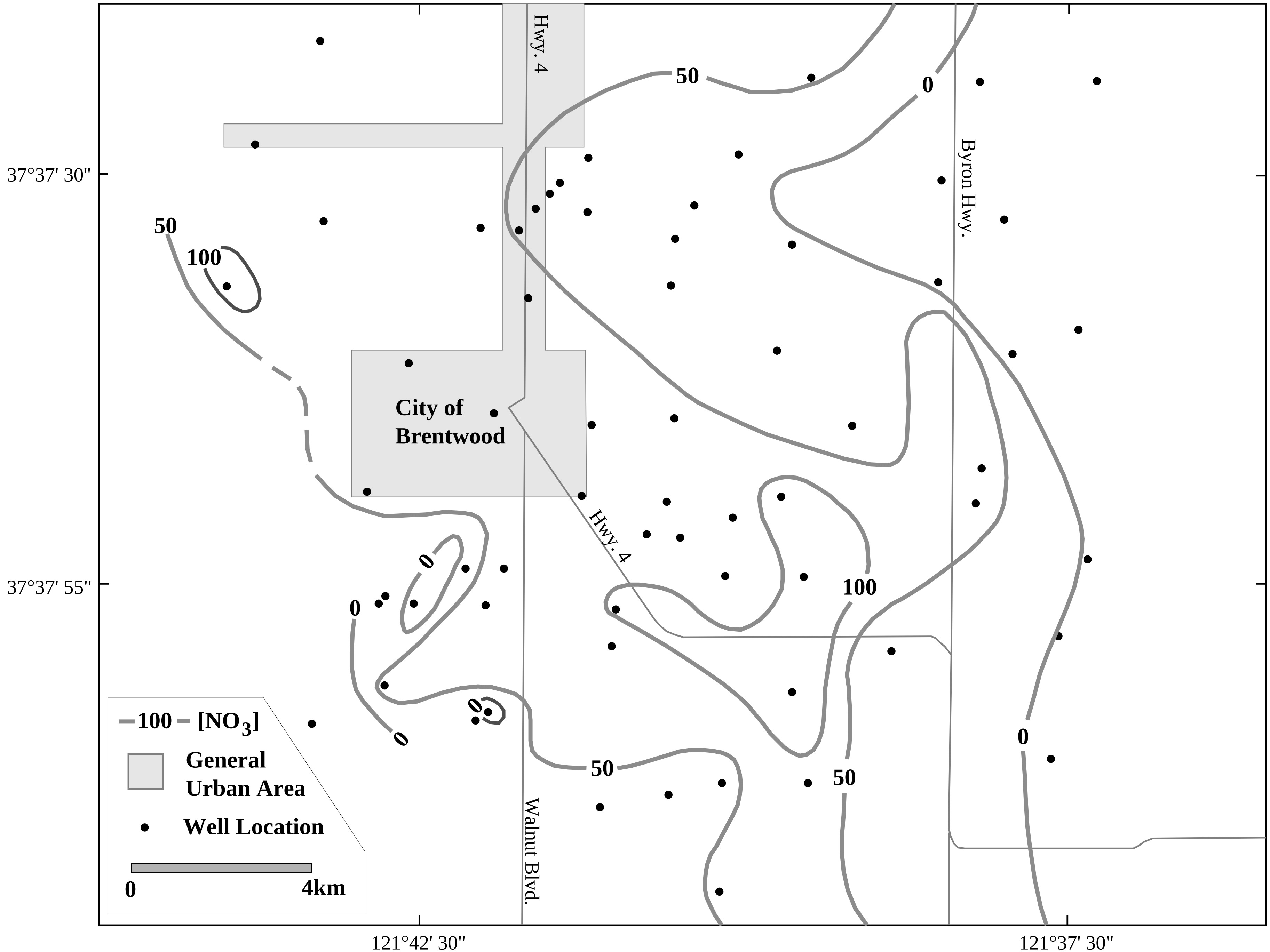
that originates from pumped, pristine groundwater sources that has evaporated during flood irrigation [see ref. 2].

Figure 5. As urban areas encroach on agricultural land, reduced safe-yields will result due to the loss of flood irrigation, which has been the principal source of recharge during recent decades. The Brentwood region totals 67km^2 with a current agricultural to urban land use ratio of 15:1. By the year 2020, the ratio is expected to be close to 1:1. The population increase was calculated by assuming 2175 people per km^2 in an urban development scheme, and the inflection point in the trend is where urbanization begins to encroach on the agricultural areas underlain by tile drains in the northeastern parts of the Brentwood region.

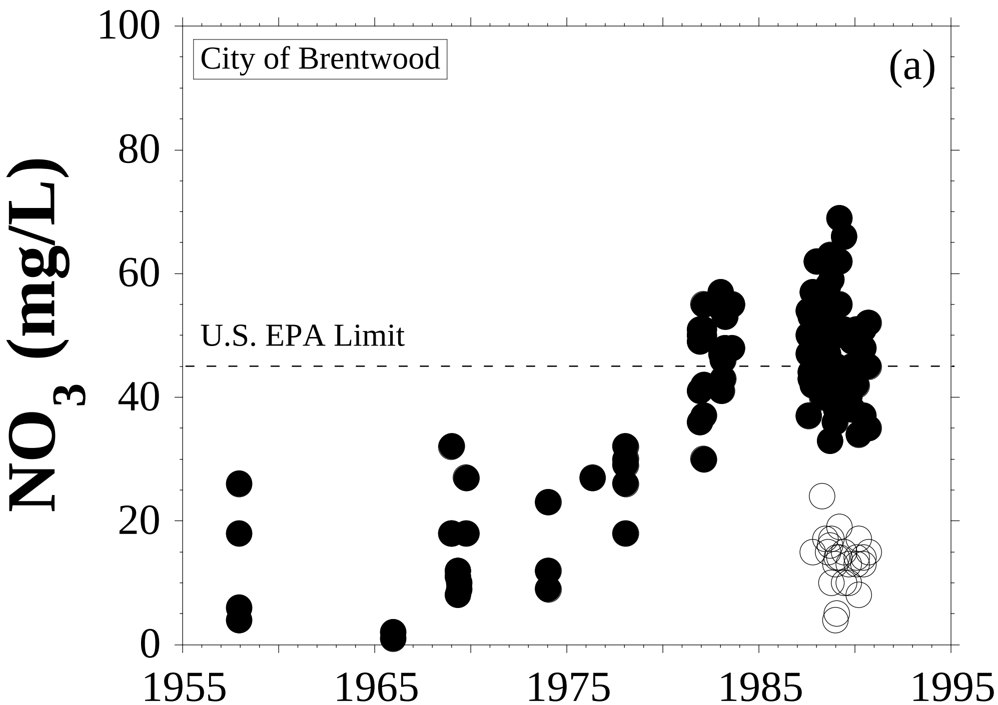


Sutter Buttes
Yuba City
Sacramento River
Yolo County
Lake Berryessa
Cache Cr.
W
Davis
Sacramento
American R.
Fairfield
Sacramento R.
Sacramento-San Joaquin Delta
Mokelumne R.
Stockton
Mt. Diablo
Brentwood Region
San Joaquin River
Nevada
California
Study Area
Urban Areas
Constant δ18O
0
30 km
-9
-8
-7
-6

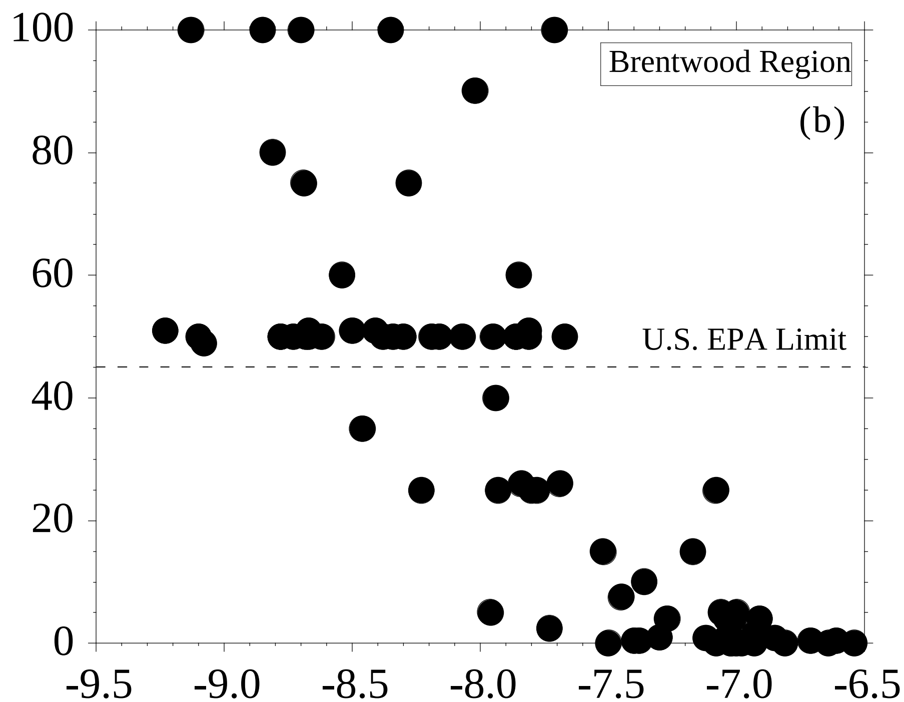

Model ^{14}C age
16000
12000
8000
4000
0
0
100
200
300
400
Depth (mbs)
Sacramento
Yolo County
Brentwood Region



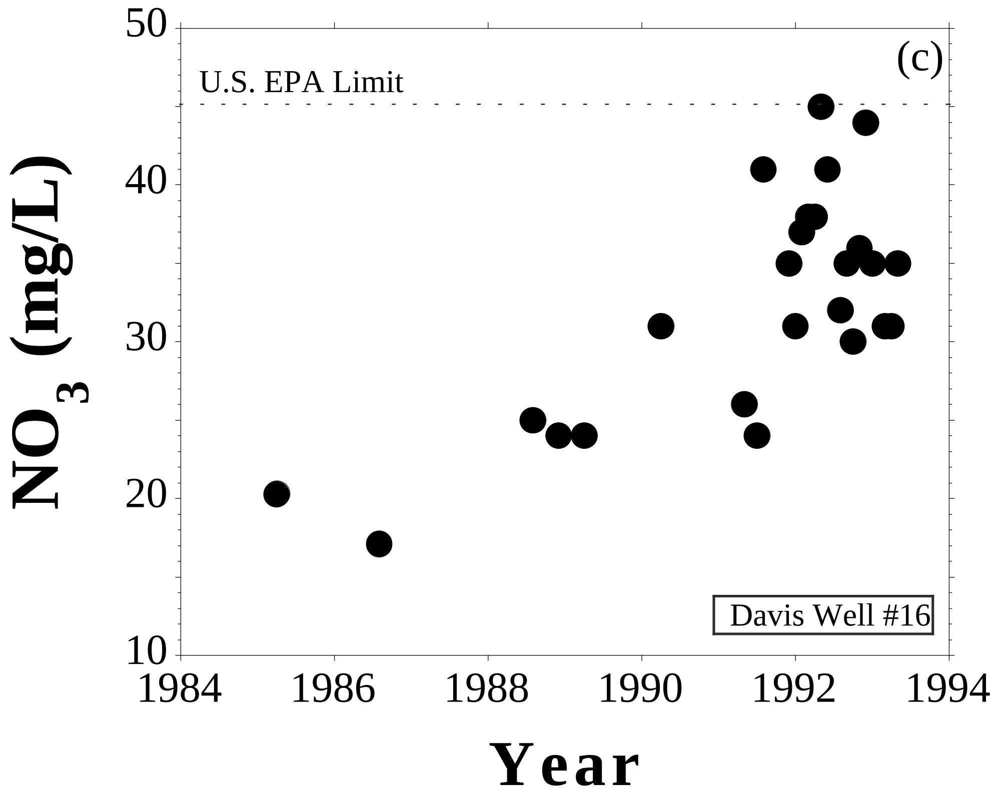
Hwy. 4
Byron Hwy.
Walnut Blvd.
City of Brentwood
50
100
0
37°37' 30"
37°37' 55"
121°42' 30"
121°37' 30"
100 [NO_3]
General Urban Area
Well Location
0
4km



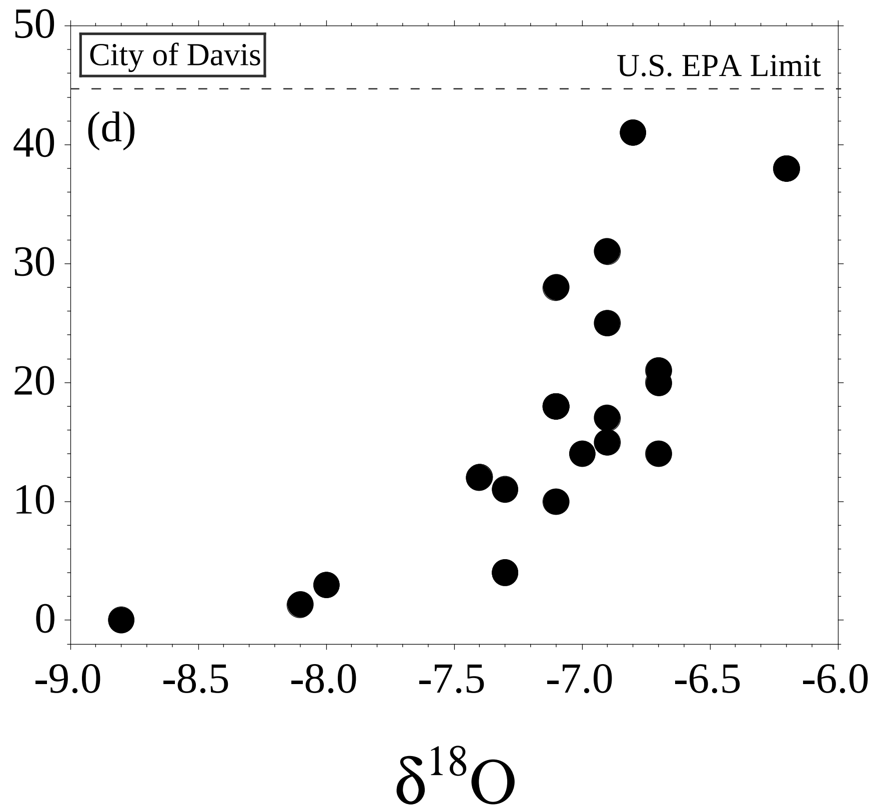
City of Brentwood
(a)
U.S. EPA Limit
NO_3 (mg/L)
0
20
40
60
80
100
1955
1965
1975
1985
1995



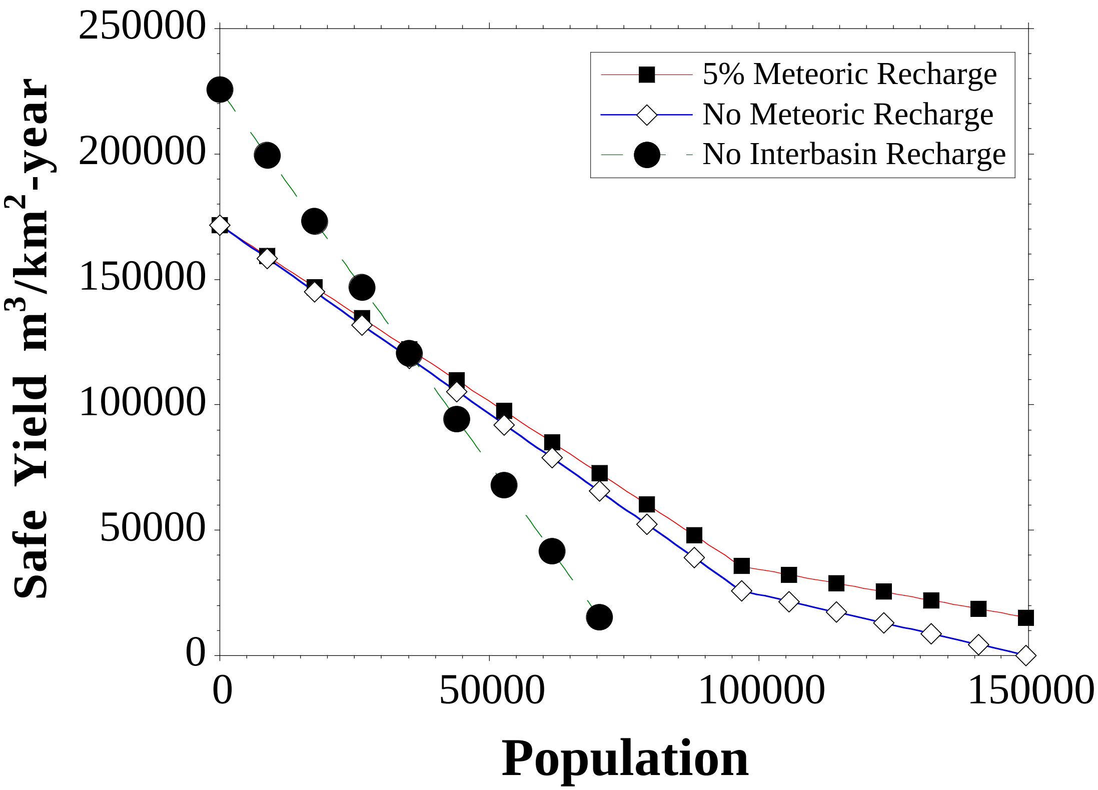
100
80
60
40
20
0
-9.5
-9.0
-8.5
-8.0
-7.5
-7.0
-6.5
Brentwood Region
(b)
U.S. EPA Limit



50
40
30
20
10
1984
1986
1988
1990
1992
1994
(c)
U.S. EPA Limit
Davis Well #16
NO3 (mg/L)
Year



City of Davis
U.S. EPA Limit
(d)
50
40
30
20
10
0
-9.0
-8.5
-8.0
-7.5
-7.0
-6.5
-6.0
δ18O



5% Meteoric Recharge
No Meteoric Recharge
No Interbasin Recharge
Safe Yield m3/km2-year
Population
0
50000
100000
150000
200000
250000

Table 1: Pristine Groundwaters of the Central Valley

Sample	Apparent Age	Model Age	d13C	Avg. Perforation Depth (mbs)	Distance From Edge of Valley (km)	Perf. Depth/Model Age
City of Sacramento						
SCW-41	15,490	1,873	-25.2	77	20.92	0.041
SCW-85	8,711	3,304	-20.2	73	20.92	0.022
Yolo County						
DCW-22	3,740	2,432		114	23.99	0.047
DCW-19	3,461	2,155		91	20.48	0.042
DCW-21	4,130	2,825		101	23.99	0.036
DW-6A	10,629	9,332		373	21.07	0.040
DW-5	13,653	12,337	-13.9	376	21.07	0.030
DW-2	16,985	15,660		361	21.07	0.023
DW-3	15,551	14,262	-13.8			
10N1W2Q1	8,207	6,901		79	19.31	0.011
SV-JF-9-91	16,321	15,022	-12.7	107	14.63	0.007
P-1	7,636	6,321	-9.8	240	11.70	0.038
P-2	5,744	4,441	-10.1	179	11.70	0.040
P-3	5,109	3,810		117	11.70	0.031
P-4	6,275	4,967	-11.4	58	11.70	0.012
Brentwood Region						
BR-14	5,335	4,025	-13.8	44	6.44	0.011
BR-21	4,500	3,196		85	3.22	0.027
BR-38	3,009	1,699	-12.5	40	0.80	0.024
BR-62	5,579	4,279	-11.5	81	6.44	0.019
BR-63	7,911	6,595	-15.0	34	6.44	0.005
BR-65	3,306	1,996	-12.6	41	7.24	0.021
BR-66	5,786	4,474	-13.3	87	7.24	0.019
BR-69	3,800	2,496	-12.8	76	8.05	0.030
BR-70-1	1,536	230	-11.2	40	1.61	0.174
BR-73	9,949	8,638		94	7.24	0.011
BR-88	13,009	11,704	-13.9	96	8.05	0.008
BR-18	2,541	1,234	-12.5	91	3.22	0.074
BR-55	5,103	3,795		46	4.47	0.012

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